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PROGRESS IN THE NONDESTRUCTIVE EVALUATION OF CF-18 COMPOSITE FLIGHT CONTROLS FOR WATER INGRESS AND RELATED DAMAGE

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Progress in the Nondestructive Evaluation of CF-18 Composite Flight Controls for Water Ingress and Related Damage

by

Capt B.A. Lepine and K.I. McRae

Introduction

In late 1995, the CF Nondestructive Testing Center (NDTC) at the Aerospace and Telecommunications Engineering Support Squadron (ATESS) in CFB Trenton arranged for a CF-18 to be sent and tested at the neutron radiography and X-ray facility at McClellan AFB, Sacramento, CA. As indicated in the subsequent inpection report (ref 1), it was discovered that the right aileron and the left rudder had indications of moisture ingress in the graphite/epoxy skin layers or aluminum honeycomb core structure, as well as the possibility of corrosion in the core. After further NDT inspections of the rudder coordinated by ATESS at the Quality Engineering Test Establishment (QETE) and the Royal Military College of Canada (RMC), the skin was removed in the affected area to allow a physical assessment of the damage by QETE. Initial results indicated that the FM-300 bonding layer had broken down at the interfaces between the aluminum cells and the adhesive and that water was present in the cells, although corrosion products were not found. More details were presented in QETE's final investigation report (ref 2), but the exact mechanism of water ingress could not be determined, and is still a mystery; several possible water/moisture entrance points have been explored.

In light of the increasing numbers of similar encounters by other F/A-18 users, it was agreed at a subsequent meeting chaired by DAEPM(FT) 2-3-6 (ref 3) that this type of problem could be spread widely in the CF-18 fleet composite flight control surfaces. Consequently, a Flight Control Inspection Program (refs 3 and 4) was initiated with the goal of assessing the extent of the problem in the fleet, investigating alternative NDT methods and identifying methods that could eventually be used by Main Operating Bases (MOBs) to detect this and other related types of defects. A concurrent, but longer term goal would be to acquire a better understanding of the mechanism causing this damage. The Air Vehicles Research Detachment (AVRD) was assigned the responsibility of coordinating the investigation of the various NDT techniques, thereby collating and analyzing the results from the various sources, reporting on the condition of the inspected components and on the effectiveness of each technique. Furthermore, the structural integrity investigators would be provided with the data needed for evaluating the effects of water/moisture on the control surfaces. This project was to take advantage of an on-going Aircraft Sampling Inspection (ASI) where 10 aircraft were to have the flight controls removed and available for short periods of time.

This report describes the condition of the flight controls from three full ASI aircraft and the rudders from three other aircraft based on the NDT indications provided by RMC's neutron radiography inspection system, operated by qualified NDT technicians from ATESS, QETE's through-transmission ultrasonic system, and Canadair's conventional X-ray inspections. Much of the material in this report was previously presented by AVRD at a review meeting last May 1997 (ref 5). An evaluation of each technique for each type of defect is also presented. Due to equipment upgrade requirements at both QETE and RMC, the Flight Control Inspection Program has been placed on hold until the summer of 1998. In addition, the ASI program has been canceled by the CF-18 AEO office, thus all future flight controls will come from stored aircraft as well as those undergoing periodic inspections.

Test Specimens and NDT Procedures

The CF-18 aircraft bears 12 flight control surfaces, each consisting of an aluminum honeycomb core with either an aluminum or graphite/epoxy skin, depending on the component. The pairs of flight controls that were inspected as part of this project are shown schematically in figure 1. Note that the horizontal stabilizers were too large to be part of this project. A drawing of a CF-18 rudder is accompanied by a cross section display in figure 2 to illustrate the typical skin and core structure of a flight control surface.

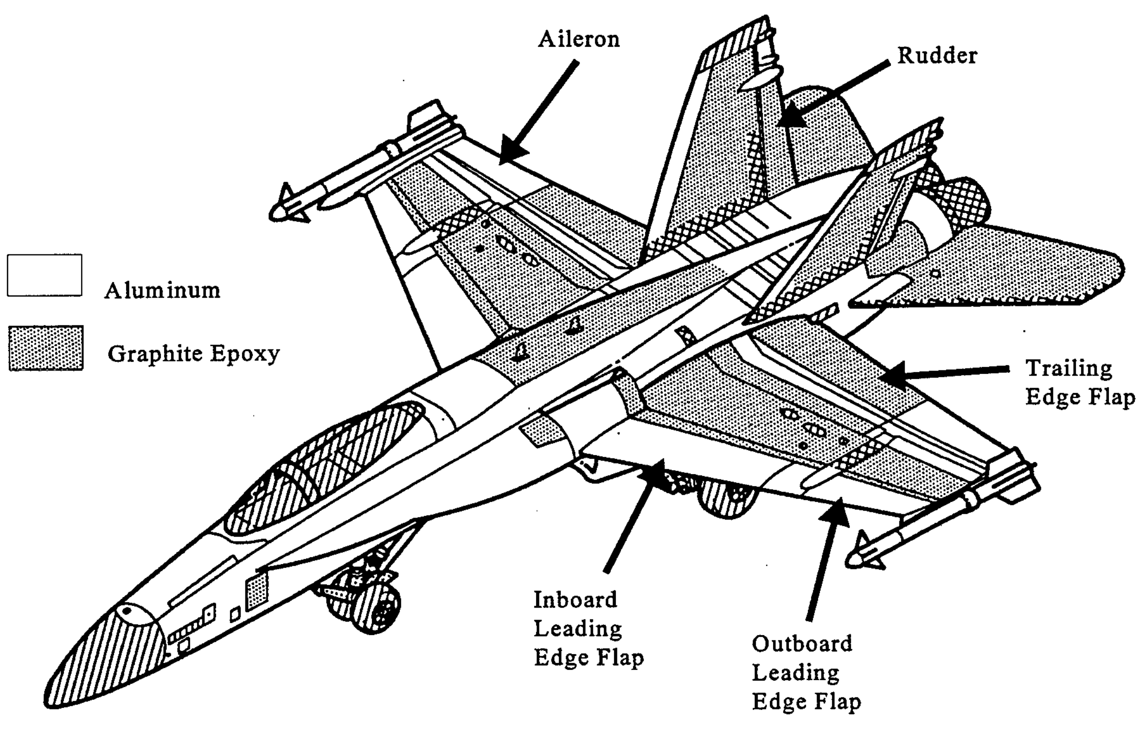


Figure 1 - CF-18A Material Distribution and Flight Controls

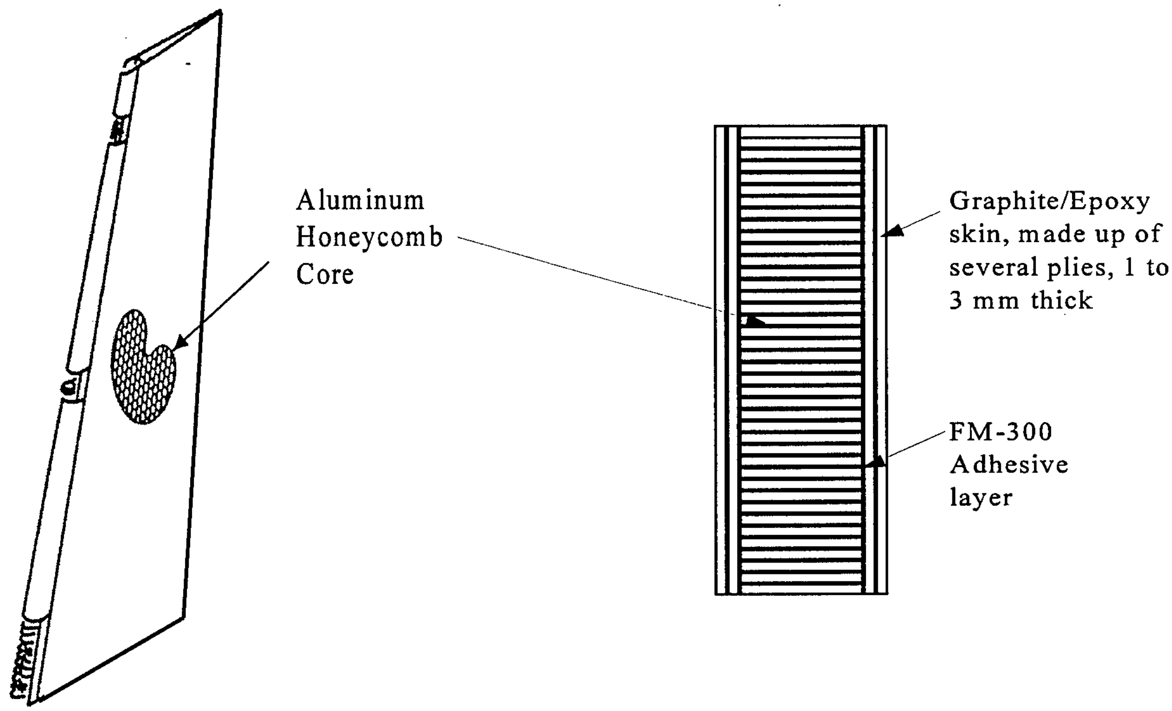


Figure 2 - CF-18 Rudder and its cross section

The NDT techniques used in this evaluation consisted of the following:

a. Neutron radiography (RMC Slowpoke-2 facility). N-ray can provide indications of water and low moisture levels in these control surfaces and can potentially detect corrosion products and certain types of sealants. This is attributed to the neutron's characteristic attenuation by elements with low atomic numbers, such as hydrogen. Radiographic film has been used for the inspections.

b. Through-transmission ultrasound (QETE water-jet-coupled large area scanner). The UT scanner can detect any condition that changes the sound attenuation properties through the thickness of the component. Hence, since a disbond increases the attenuation, the ultrasound signal will decrease; but if water fills a honeycomb cell, its attenuation is decreased, and the signal increases.

c. X-ray radiography (X-rays performed mostly by NDT technicians at Canadair, but some were also done at QETE, AVRD and ATESS for validation). This conventional method provides radiographic film indications of changes in material density as they relate to the X-rays' attenuation characteristics. Water in the honeycomb cells, for example, will have a higher density than those without; given sufficient attenuation, the water will be detectable.

Results and Discussion

a. Defect report according to NDT indications.

The entire database of results will not be presented in this report. Instead, a summary of the findings is found in table 1. Some sample images of the various NDT methods are found in annex A. These were specifically chosen to illustrate both the commonalities and differences between the types of defects detected by each technique, hence only those anomalies that were detected by all three techniques are illustrated in the annex.

Table 1 - Defect summary by aircraft tail number (188xxx)

	Rudder		Aileron		T.E. Flap		L.E.Flap(in)		L.E.Flap(out)	
Defect Type	LH	RH	LH	RH	LH	RH	LH	RH	LH	RH
Moisture or Water Ingress	729 912 902 733 736	720 708	729 708	708	708	729				
Blown or Damaged Honeycomb Core	902		708			729				
Disbond	729 733 736			708		729				
Cell Corrosion	729 912 902 733 736	708	729 708	708	708	729		708		
Suspect Areas					708	729 708		729 912(2) 708	729(3) 912(3)	708
Adhesive or Sealant Discontinuity				729	708	729 912 708				
Hinge/honeycomb Damage				729						
Repairs		729	729			729		912		
FOD					729(2) 708					

In addition, annex B lists all the NDT data files acquired to date and cross-references them to the type of damage the inspectors indicated in the reports listed in refs 6 to 11. These files are either bitmap or TIFF images that were produced by digitizing the results at QETE, RMC, ATESS, or AVRD. Most of the X-ray films were provided by Canadair, with an oral report, and subsequently digitized at AVRD.

Including the X-ray and N-ray inspections done on one entire aircraft at McClellan AFB, the flight controls inspected to date number as follows: 13 rudders, 8 ailerons, 8 trailing edge flaps, and 8 inboard and outboard leading edge flaps. Of these, 7 rudders (54%), 4 ailerons (50%), 2 trailing edge flaps (25%), and 1 inboard leading edge flap (13%) were identified as having some level of moisture, water ingress or related damage, not including suspect areas. The rudders have the most serious problems with water related damage near the top hinge and leading edge of the component, usually in the form of large amounts of water in the cells, or disbonds in the same locations.

b. NDT correlation with destructive analysis and structural implications.

Some NDT results on the rudders were confirmed by subsequent de-skinning of two rudders at Canadair for QETE. Destructive analysis revealed the presence of water in the cells in exactly those locations indicated by N-ray, X-ray and in some cases UT. Disbonds, caused by the hydration of the FM-300 adhesive layer and eventual break down of its bonding characteristics, were also confirmed in three different locations previously identified by UT. However, cell corrosion has yet to be detected by destructive means. Consequently, any cell corrosion calls made by the NDT techniques may be inaccurate, considering that none of the destructive analysis performed on rudders with the most advanced stages of damage revealed any form of corrosion product. In addition, there were several "suspect areas" called by the N-ray method which have not been physically identified. It is also worth noting that the water entrance points and mechanisms have not been identified conclusively at this time.

Although some rudders have been de-skinned and destructively analyzed, more evaluations of this type are required to completely validate the calls and interpretations given by all the NDT techniques. In particular, the N-ray technique is still very new and the expertise in this area is increasing; hence calls will most likely become more accurate and definitive with experience and with more numerous and detailed sample analysis.

The nondestructive and destructive testing data have revealed that relatively large areas of disbonds occur before any significant amounts of corrosion; therefore, the skin-to-core disbond by adhesive bond failure is considered as the most serious failure mode detected. Considering the limited efforts so far on failure analysis, however, there is still a need to study the effects of these bond failures as well as any other possible failure modes and mechanisms. These can include the moisture levels in the honeycomb and in the composite skin, the hydration of the adhesive since that affects bond strength, cell corrosion that may eventually occur, and aluminum cell node unbonds. Additional studies of the breakdown of the water entrance paths and the effects of freeze/thaw cycles of the water in the cells may also be required. Of course, the implications of these modes on the components' structural integrity need to be understood if the maintenance actions, NDT, repairs or replacements are to be cost effective.

In summary, for all of these modes, some kind of criticality assessment is required that can ultimately identify maximum allowable limits and develop short and long term detection criteria and repair schemes. For example, a simple short term solution may arise that requires a field capable technique to detect disbonds and/or water filled cells larger than a given area, and the repair scheme may simply be based on the size of the affected area. If necessary, longer term activities could focus on more quantitative NDT approaches once the structural analysis identifies those areas that need to be accurately assessed, such as corrosion damage, quantitative disbond or low moisture measurements. This could lead to the development of a condition based off-aircraft inspection routine, where a suspect component inspected in the field with more serious indications could be sent to a facility with more sensitive NDT equipment for quantitative evaluation, such as N-ray.

c. Evaluation of NDT methods by defect type (refer to table 2)

Moisture and water ingress. Neutron radiography is capable of detecting water in the cells as well as extremely low levels of moisture, such as cell hydration. X-rays can detect significantly higher levels of moisture, such as partially to fully filled cells. However, the technicians at Canadair have optimized the X-ray methods to detect relatively low levels of water, as shown in annex A, but the sensitivity does not reach that of N-ray. A quantitative assessment of both these methods would better evaluate their effectiveness, which would prove useful if a detection criteria was implemented. Some UT scans have indicated water ingress, most likely due to the increased sound propagation through the cells completely filled with water. It may also be suggested that UT can detect density changes of the hydrated FM-300 adhesive, thus giving a measure of the residual bond strength, but the data herein cannot support such a conclusion.

Disbonds. Ultrasonic scans are most capable of detecting disbonds. Neither N-rays nor X-rays are able to detect disbonds directly; however, other detectable collateral anomalies may be present that are associated with disbonds. More specimens need to be inspected and analyzed to determine these, if any, associations.

Core damage. X-rays are routinely used in the field to inspect for core damage, and the results herein support it as the most effective technique for this defect type; however, an N-ray technician also has the potential to detect core damage with proper training and experience. Ultrasound will only detect core damage if it is accompanied by a collateral disbond between the skin sheet and the core.

Corrosion, and other suspect areas. Only N-rays and X-rays have the potential for detecting corrosion, but the calls reported herein have not been confirmed and cannot be evaluated.

d. Correlating the NDT methods.

N-rays always showed indications in those same areas as UT or X-ray, but the actual damage type may be hard to call (for example, disbonds or blown core damage may be identified as suspect areas). The UT and X-ray results are sporadically related, since it depends on whether both disbonds and water filled cells are present. Lastly, X-ray water indications will always be supported by N-rays, but the reverse is not true.

Examining the entire NDT data closely, there may be a relationship between the indications found from one method and another related defect that is not directly detected, except by other methods. In a sense, we may be able to suspect certain forms of defects when detecting another form of defect. Presently, there is not sufficient data to make such a correlation, thus more specimens are required for better evaluation. For example, in every case except one, a disbond was accompanied by water or low levels of moisture. However, the opposite is not true. In summary, all the NDT methods compliment each other, and none stands out as the one and only solution to this NDT problem.

Table 2 - Summary by NDT Technique

Defect Type	T.T. Ultrasound	X-Ray Rad.	Neutron Rad.	**Total defects**
Moisture or Water Ingress	2 *	5 *	12 *	12
Blown or Damaged Honeycomb Core		2 #	1	3
Disbond	5 #			5
Cell Corrosion		1	11	12
Suspect Areas	see repairs		9 ** @	9
Adhesive or Sealant Discontinuity	1 **	1 **	4	5
Hinge/honeycomb Damage		1		1
Repairs	1 + many others suspect @		3	4 (plus others unreported)
FOD			2	2
Total Calls	9	10	42	

*, **, @ - Identical defects were identified by the indicated techniques
- N-rays called these as moisture or suspect areas

Recommendations

This project must continue to apply sensitive N-ray methods, along with UT and the field oriented X-ray method for several more sample aircraft in order to accurately determine the condition of the fleet and the effectiveness of each NDT technique. It was originally suggested early in this program that a minimum total of 10 aircraft be inspected to achieve this goal. The data could then be used by the structural integrity engineers to establish a detection criteria. If a field NDT technique is to be developed, for instance, it is first necessary to evaluate exactly which mode of failure and extent or size of defects should be detected at the MOBs to ensure that the component is airworthy. Example parameters to consider in such an exercise are as follows: the amount of water in the cells, the number of cells that contain water (or the area size with water filled cells), the affected area size of disbonds, and the level of moisture in the FM-300 adhesive. It may also be beneficial to include an NDT portion to a structural integrity analysis project to cooperatively evaluate both issues using shared resources. In addition, there needs to be more efforts in correlating NDT data with actual destructive analysis to validate all these NDT methods. This can take place either on CF components that require repairs, or on those from external sources such as from foreign military users that discard damaged components more readily than the CF.

More detailed long term recommendations can be suggested after the next phase (completion of 10 aircraft) of this program.

Conclusions

Several CF-18 flight controls were inspected for water ingress related damage using three NDT methods: X-ray, neutron radiography, and through transmission ultrasonics. The NDT results to date show that various stages of failure modes may exist in the fleet, some of which are advanced to the stage of disbonds which could, if untreated, progress further to point of possible in-flight skin failure. Of all the components, the rudders have the most serious problems with high moisture levels in the honeycomb core and/or disbonds near the top hinge. About 50% of the rudders inspected have some type of moisture related damage. Although the N-ray technique reported several corrosion indications, destructive analysis performed on two rudders with some of the most advanced stages of damage revealed no evidence of corrosion products.

All three NDT methods can detect certain stages or types of damage, but none can detect all the damage; in effect, they are complimentary to each other. The NDT methods gave qualitative results, thereby providing images of the indications on film or digitized formats; however, more quantitative results are possible in all cases with the use of calibration techniques. The N-ray technique is the most sensitive to low level moisture, but X-rays can detect water in individual cells. Lastly, disbonds can only be detected by the ultrasonic NDT method.

References

1. Nondestructive Inspection Report on CF188733, from USAF Sacramento Air Logistics Center, McClellan AFB, CA - Volumes I and II, March 1996

2. Investigation of a CF-188 L/H Rudder Anomaly, Quality Engineering Test Establishment, April 1997

3. Corrosion in CF-18 Composite Flight Control Surfaces, 11500MD-104 (DAEPM(FT) 2-3-6), 25 June 1996.

4. CF-18 Composite Flight Controls Corrosion/Water Ingress Inspection Project - Mission Statement, 11500MD-146 (DAEPM(FT) 2-3-6), 18 September 1997.

5. CF-18 Composite Flight Controls Corrosion Inspection Program Review Meeting - 29 May 1997, 11500MD-146 (DAEPM(FT) 2-3-6), minutes 4 June 1997.

6. Project N96707E CF 188 Flight Control Inspection Neutron Radiography Report, ATESS NDTC.

7. QETE Project A023496, ASI Program/C-Scan Inspection of A/C 188729 Flight Control Surfaces, 1776 (QETE 4), 16 April 1997.

8. QETE Project A002197, ASI Program/C-Scan Inspection of A/C 188720 Flight Control Surfaces, 10081-19 (QETE 4), 5 May 1997.

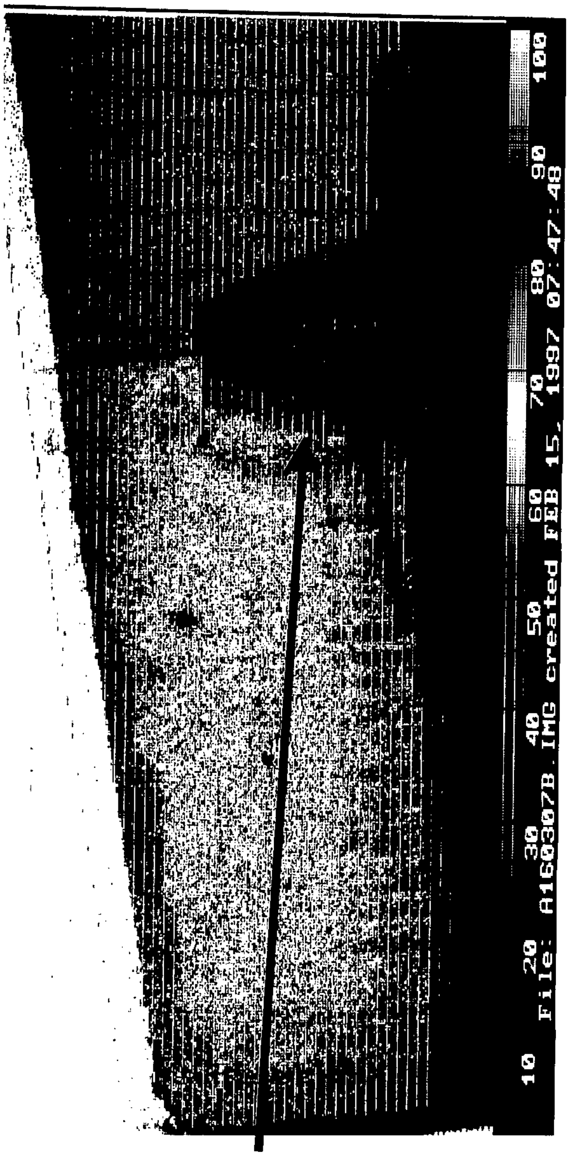
9. QETE Project A027396, ASI Program/C-Scan Inspection of A/C 188912 Flight Control Surfaces, 10081 (QETE 4), 16 May 1997.

10. QETE Project A003597, ASI Program/C-Scan Inspection of A/C 188708 Flight Control Surfaces, 10081 (QETE 4), 10 June 1997.

11. QETE Project A010097, ASI Program/C-Scan Inspection of A/C 188736, L/H Rudder, A010097 (QETE 4), 8 August 1997.

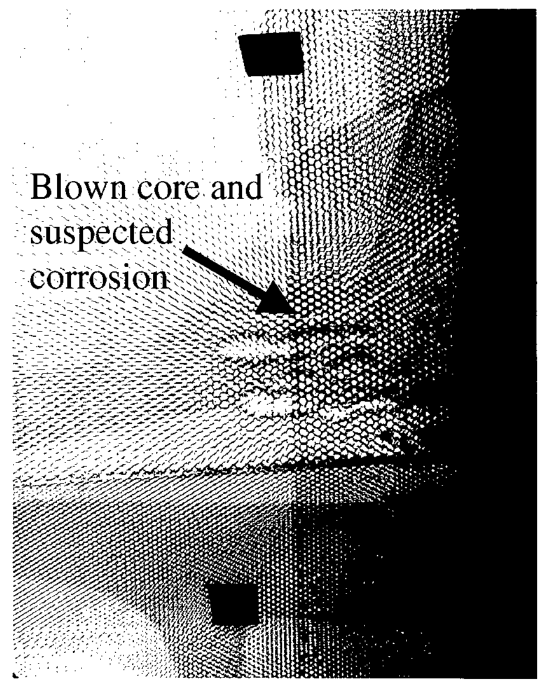
RH Trailing Edge Flap A16-0307
(Aircraft CF188729)

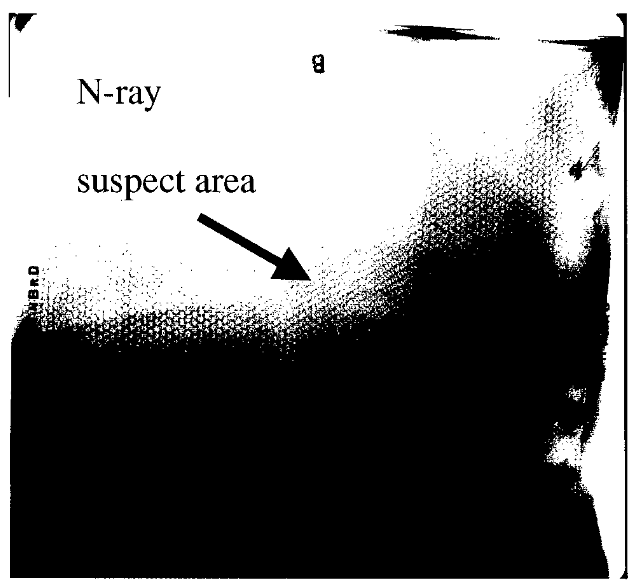
T.T. Ultrasound



Strong attenuation
indicates
large disbond

X-ray





Annex A - Sample NDT results
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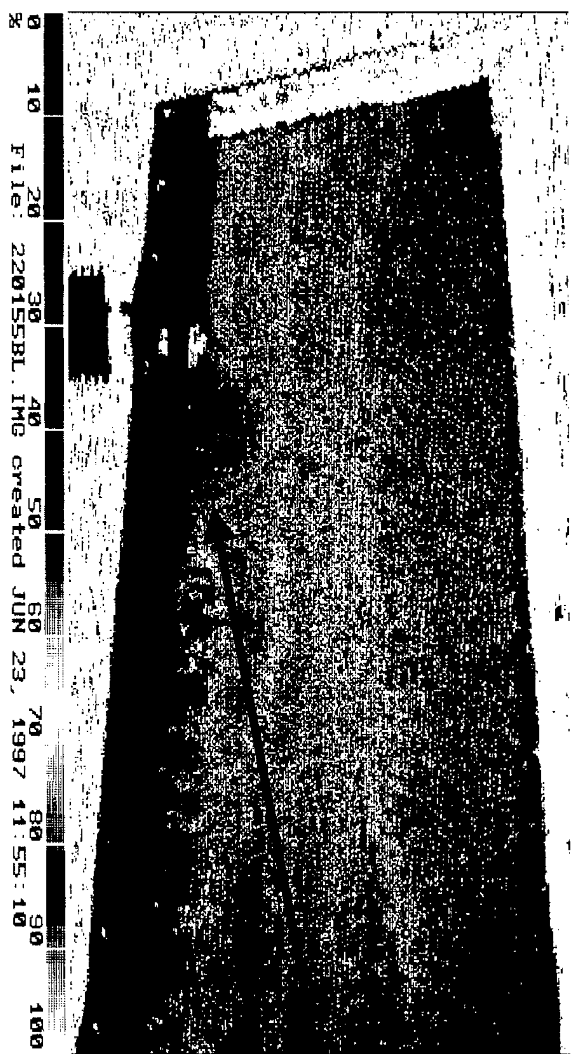
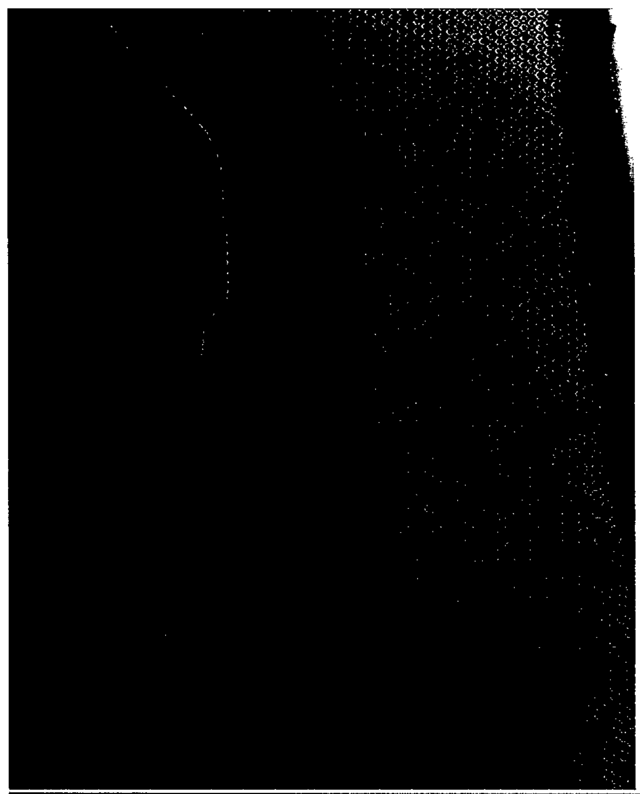
LH Rudder - U22-0155
(Aircraft CF188736)

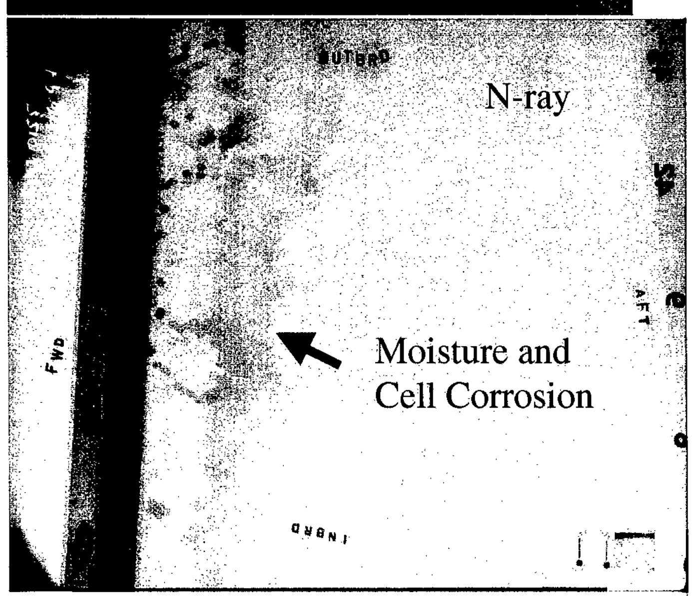
T.T. Ultrasound



Attenuation
indicates
Adhesive Disbonds

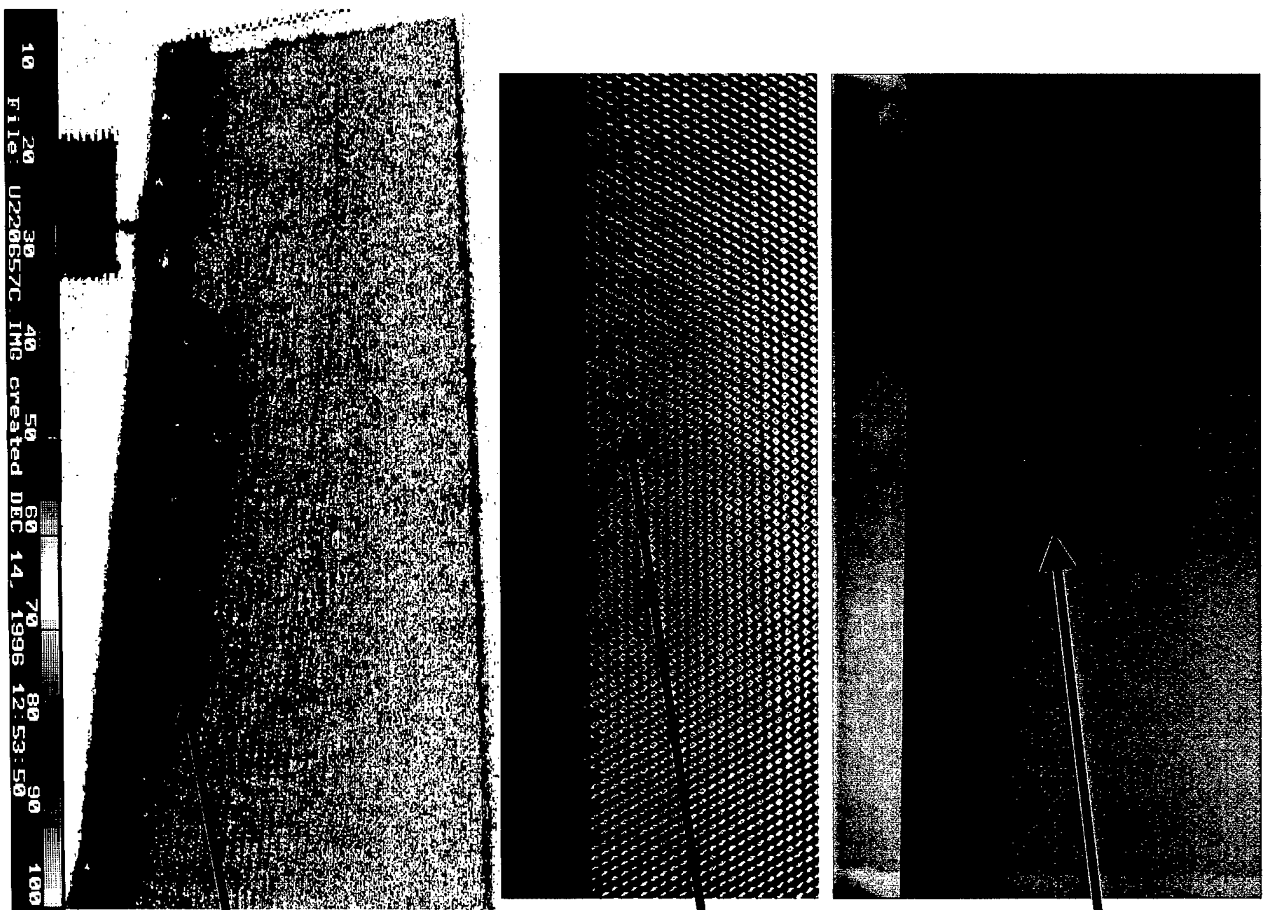
X-ray





LH Rudder - U22-0657
(Aircraft CF188729)

T.T. Ultrasound | X-ray | N-ray



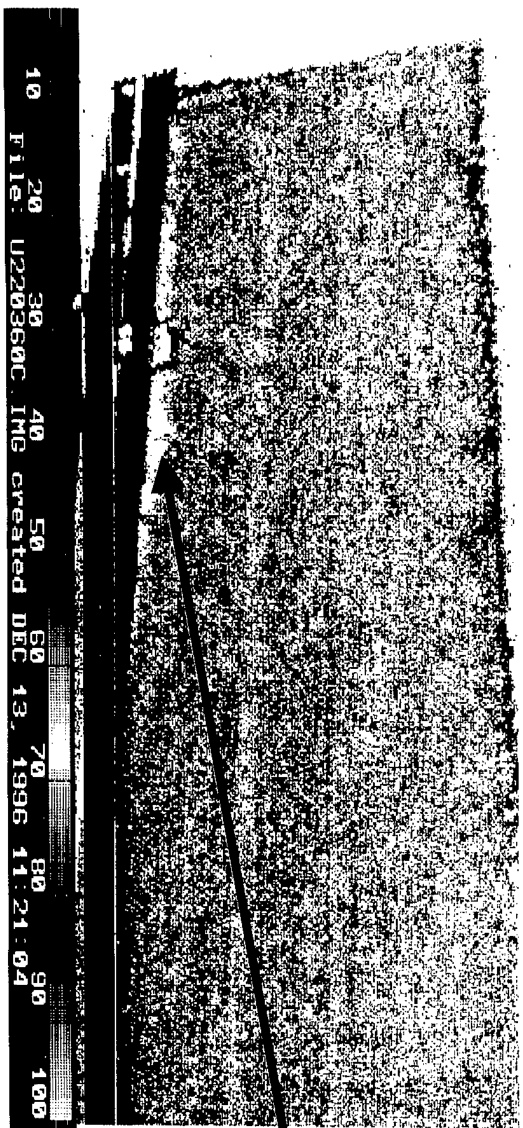
Attenuation indicates Adhesive Disbond

Water Ingress

Moisture / Water Ingress

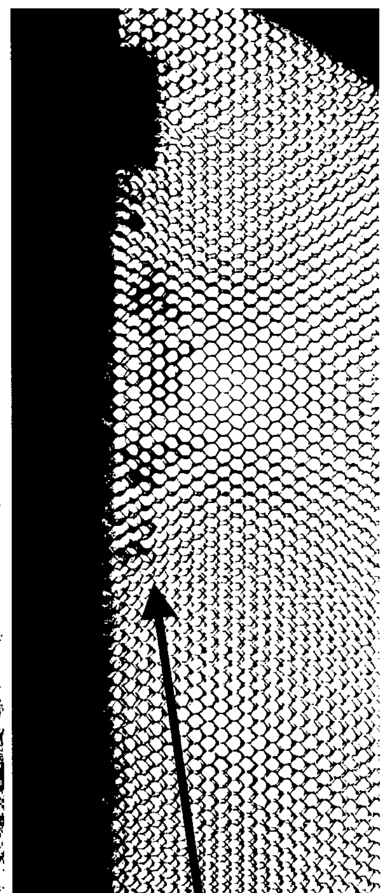
RH Rudder - U22-0360
(Aircraft CF188720)

T.T. Ultrasound



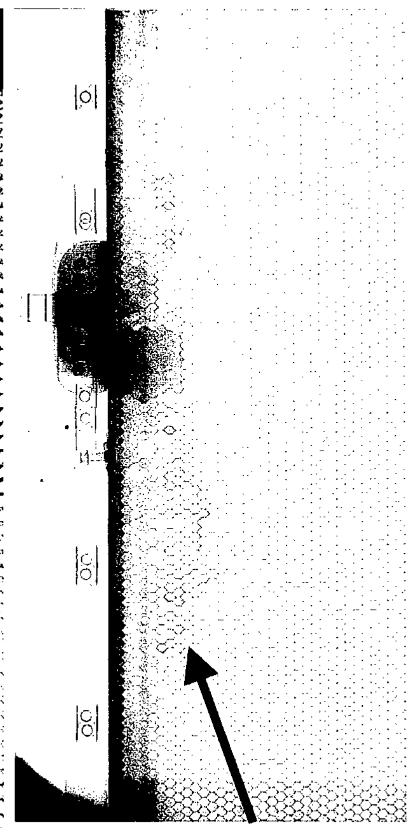
Water filled cells indicated by lower attenuation (white)

X-ray



Water Ingress

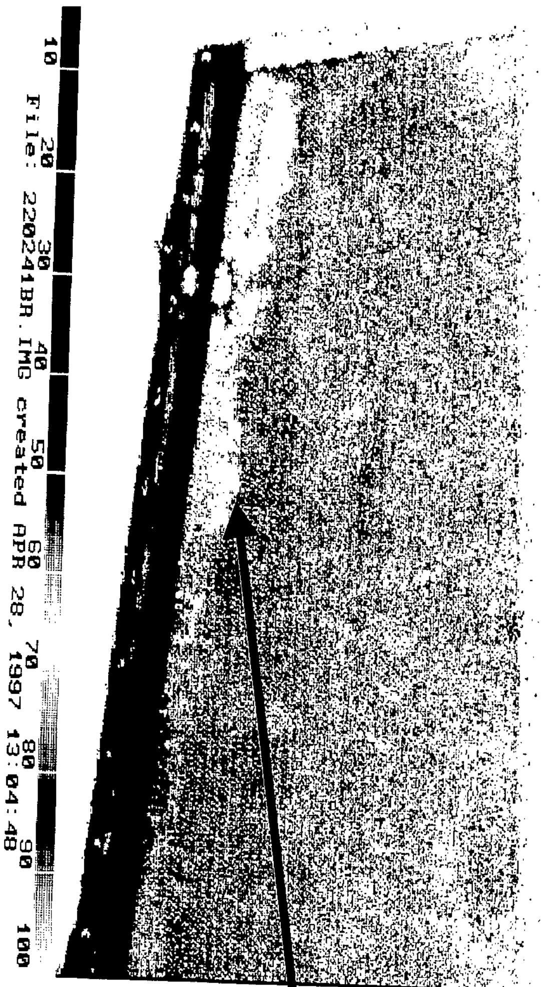
N-ray



Moisture / Water Ingress

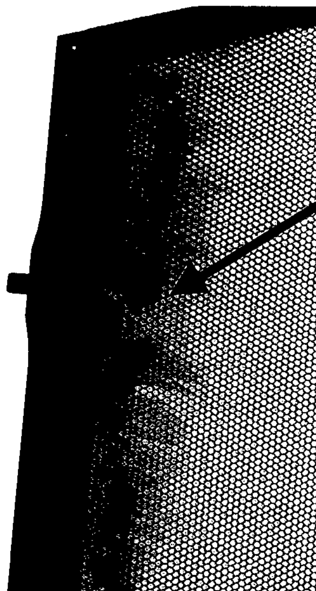
RH Rudder - U22-0241
(Aircraft CF188708)

T.T. Ultrasound



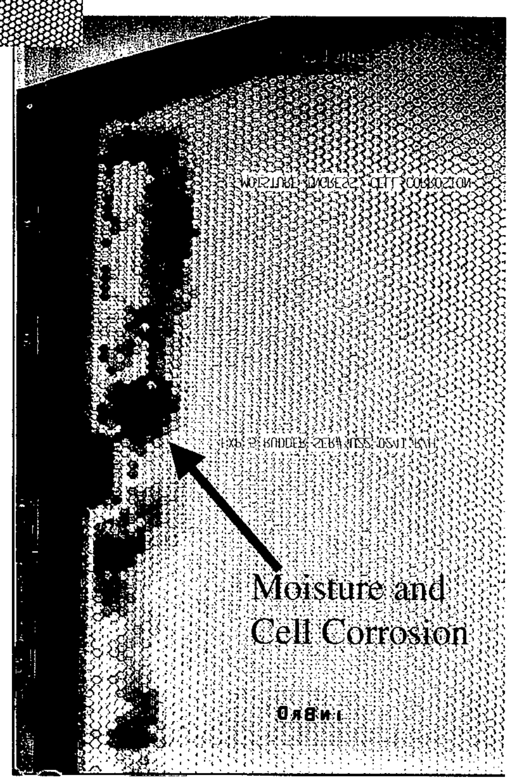
Lower attenuation
indicates
Water Ingress

X-ray



Water
Ingress

N-ray



Moisture and
Cell Corrosion

A/C number	Flight control	Serial Number	Type of damage	N-ray	X-ray	UT C-scan	Comments
188708	LH aileron	A18-0105	crushed core	*x21aal05			* this image is only in hardcopy
(entire a/c)			moisture and cell corrosion	x31bal05			
(except H-stab)	RH aileron	A18-0498	moisture and cell corrosion	x31aal98			
			disbond			**uail0498	** further X-rays at QETE revealed disbond was due to water ingress
	RH Rudder	U22-0241	moisture and cell corrosion	x4r0241			
				x5r0241			
			water ingress		*xrud0241	urud0241	*using new technique with LORAD tube
	LH TEF	CR160037	moisture and cell corrosion	x6tef37			
			adhesive, and cavity	x1tef37			
			suspect area	x5tef37			
			FOD	x6tef37			
	RH TEF	A16-0029	suspect areas	x5tef29			
				x7tef29			
				x10tef29			
				x11te029			
				x12tef29			
				x13tef29			
			discontinuities (adhesive?)		***yes	utef0029	*** this x-ray image is only in hardcopy
	RH inbrd LEF	A14-0099	suspect areas	x11lef99			
				x22lef99			
			possible cell corrosion	x31lef99			
	RH outbrd LEF	A0015-0099	suspect areas	x2leo99			
188720	RH rudder	U22-0360	water and moisture ingress	nrud0360			
(only rudders)			water ingress		*xrud0360	urud0360	*x-ray performed at AVRD

A/C number	Flight control	Serial Number	Type of damage	N-ray	X-ray	UT C-scan	Comments
188729	LH aileron	A18-0209	moisture and cell corrosion	x1ail			
(entire a/c)			repairs	x1ail			
(except H-stab)	RH aileron	A18-0209	inconsistency in sealant	x21aal09			
			damage to hinge attachment	hingeal			
	LH rudder	U22-0657	moisture and cell corrosion	x5dr0657			
			water ingress		*xrud0657		*using new technique with LORAD tube
			partial disbond			urud0657	
	RH rudder	U22-0256	repairs	x4r0256			
	LH TEF	CR160011	FOD	x12tef11			
			FOD and cavity in honeycomb	x13tef11			
	RH TEF	A16-0307	possible cell hydration	x6tef07			
			suspect areas	x5tef07			
			porosity in sealant	x9tef07			
			repairs	x14tef07			
			blown core & suspect corrosion		*xtef0307		*using new technique with LORAD tube
			large disbond			utef0307	
	LH outbrd LEF	A15-0195	suspect areas	x2le095l			
				x3le095l			
				x4le095l			
	RH inbrd LEF	A14-0197	suspect area	hingelef			
188733	LH rudder	U22-0472	moisture and cell corrosion	mclelan			N-ray done at McClellan Air Force Base
(at McClellan)			large disbond			qetescan	
	RH Aileron	A17-1018	Moisture	see report			
			Moisture and cell corrosion around a repair	see report			

A/C number	Flight control	Serial Number	Type of damage	N-ray	X-ray	UT C-scan	Comments
188736	LH rudder	U22-0155	moisture and cell corrosion	x1rud736			
(only rudders)			(very severe ingress)	x2rud736			
				x3rud736			
				x4rud736			
			water ingress		*xrud0155a		*using new technique with LORAD tube
					*xrud0155b		
			large adhesive disbonding due to water ingress			urud0155a	
						urud0155b	
188902	LH rudder	U22-0268	moisture and cell corrosion	x4r0268			
(only LH rudder)			water ingress and core damage		*xrud0268		*using new technique with LORAD tube
						!!!	!!! QETE did not perform UT inspection
188912	LH rudder	U22-0211	moisture and cell corrosion	x1r0211			
(entire a/c)	RH TEF	A16-0240	voids in sealant	***yes			*** this N-ray is only in hardcopy
(except H-stab)	LH outbrd LEF	A0015-0081	suspect areas	x1le0081			
				x3lof081			
				x4le0081			
	RH inbrd LEF	A14-0089	suspect areas	x1lefi89			
				x22lfi89			
			discontinuities (repairs or adhe)			ulefi089	
					!!!		!!! Old X-ray technique was being used at Canadair at the time, and may have missed indications

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Progress in the Nondestructive Evaluation of CF-18 Composite Flight Controls for Water Ingress and Related Damage

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5. AUTHOR(S) (Last name, first name, middle initial. If military, show rank, e.g. Burns, Maj. Frank E.)

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A Nondestructive Testing (NDT) program was initiated with the goal of inspecting flight controls from several CF-18's for water ingress and related damage using three NDT methods: X-ray, neutron radiography (N-ray), and through transmission ultrasonics, all in various facilities. Based on three full sets of flight controls plus some individual rudders, the NDT results presented in this report show that various stages of failure modes may exist in the fleet's flight controls. Some of the specimens are advanced to the stage of disbonds which could, if left untreated, progress further to point of possible in-flight skin failure. Of all the components, the rudders have the most serious problems with high moisture levels in the honeycomb core and/or disbonds near the top hinge. About 50% of the rudders inspected have some type of moisture related damage. Although the N-ray technique reported several corrosion indications, destructive analysis performed on two rudders with some of the most advanced stages of damage revealed no evidence of corrosion products. It is recommended that the program continues to perform sample inspections of several more CF-18s, as more data is required to make a more definite fleet assessment. As a secondary goal, the three methods were evaluated and correlated against each other. All three NDT methods can detect certain stages or types of damage, but none can detect all the damage; in effect, they are complimentary to each other. The NDT methods gave qualitative and potentially quantitative results, thereby providing images of the indications on film or digitized formats. The N-ray technique is the most sensitive to low level moisture, but X-rays can detect water in individual cells. Disbonds can only be detected by the ultrasonic NDT method.

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Nondestructive testing
Neutron radiography
X-rays
Ultrasonics
Graphite/epoxy skin
Aluminum honeycomb core
Disbonds
Corrosion